Metrology Challenges in 450mm/10nm Era

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PDC, Applied Material

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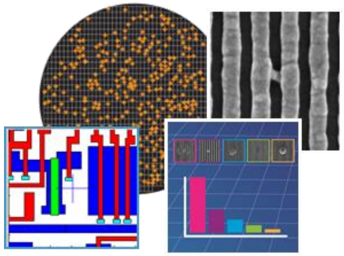
M&I Challenges and Inflections

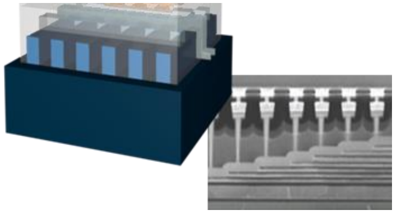
Smaller dimensions - Smaller killer Defects

- Capture defects of Interest – overwhelming % of nuisances
- Systematic defects more critical for yield control
- Optics sensitivity limitations vs e-beam throughput



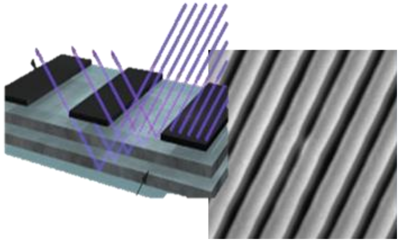
Structures and New Materials

- 3D structures (FinFet, 3D-NAND) – emerging need for HAR and sidewall imaging
- New & sensitive material



Patterning

- Litho Qual & Control – tighter process window
- Advanced masks and multi patterning
- In-die overlay is a greater challenge
- EUV mask – new challenges need higher resolution



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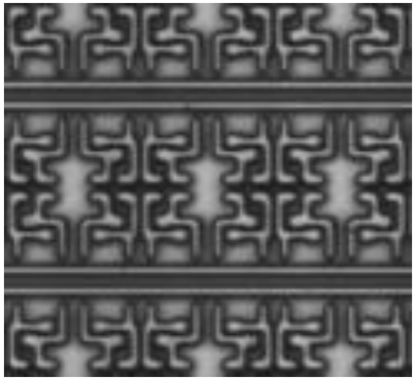
Imaging Machines – Technology Duo



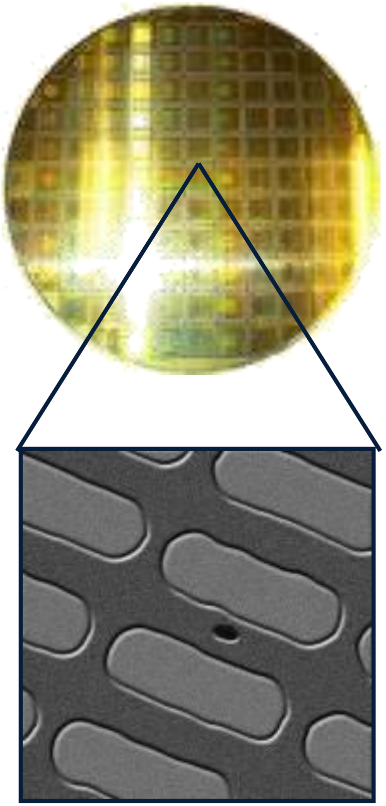
Imaging

Processing

How hard can it be?

Detecting a 40nm defect on a wafer is like …

300mm Wafer



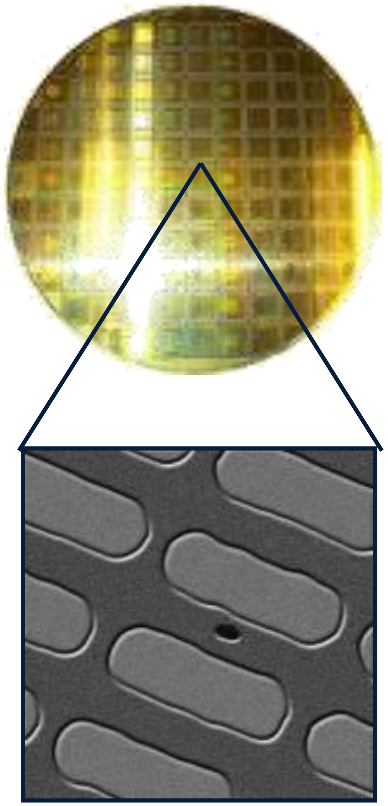
40*50nm defect

…finding an ant
in Manhattan

How Hard Can It Be?

… and still be production worthy, we should be able to…

300mm Wafer



40*50nm defect

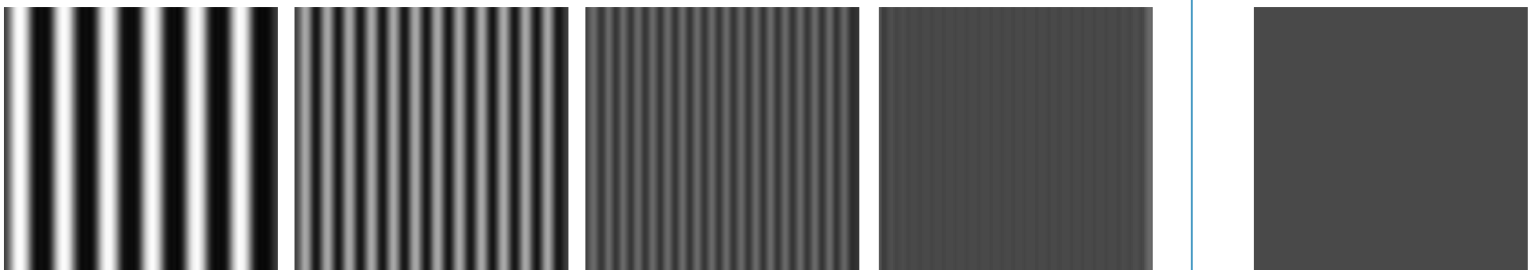
DATA RATE

…play a 50GB blu-ray movie in few seconds

Evolving Challenges in Inspection

Are we heading into a brick wall ?

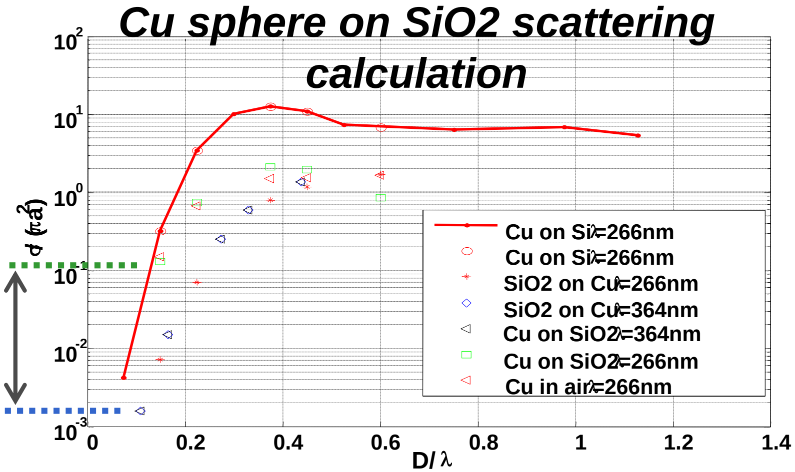
f=0.5*NA/λ | f=1*NA/λ | f=1.5*NA/λ | f=1.9*NA/λ



DR: 250nm | DR: 110nm | DR: 90nm | DR: 70nm | DR: 55nm

No Resolution

No resolution for $f > f_{cut\text{-}off} = 2NA / \lambda$

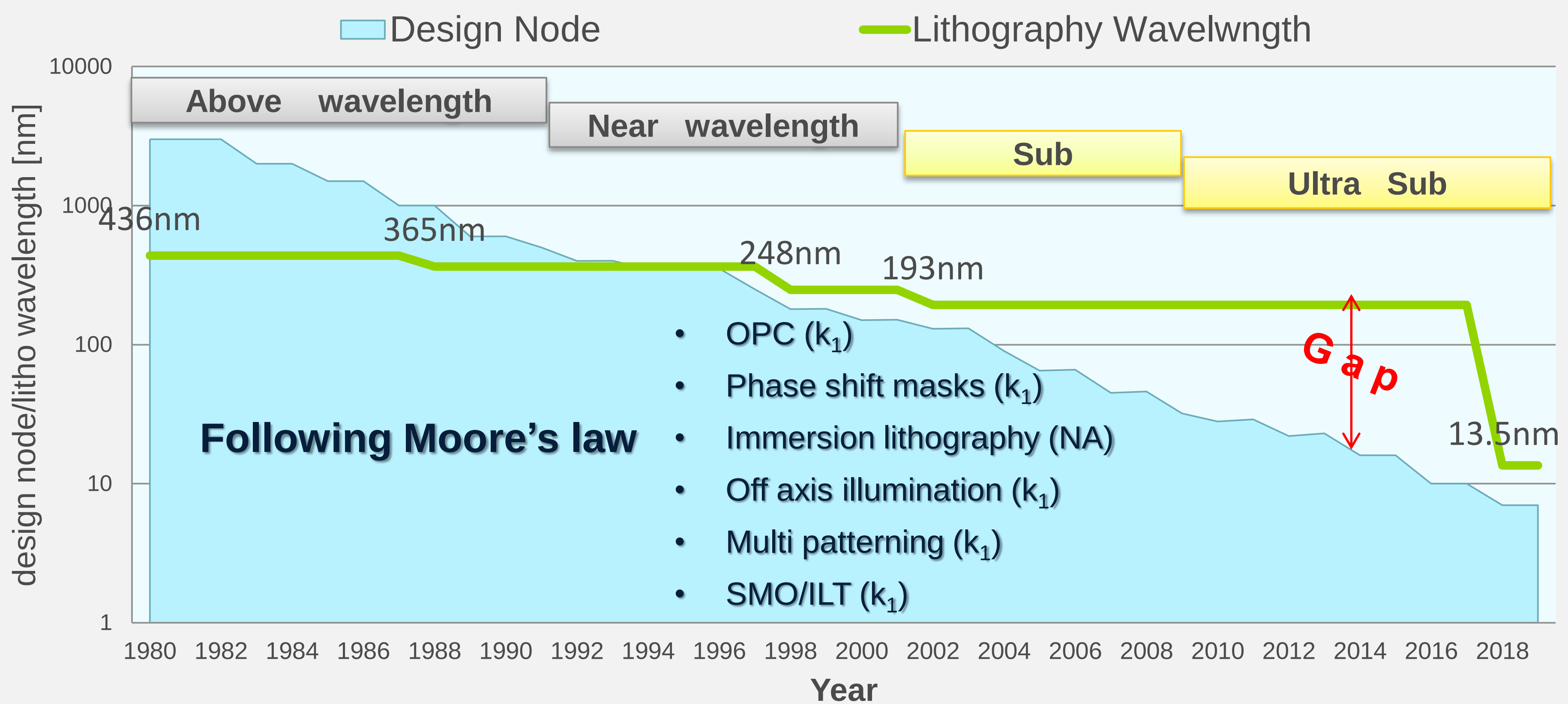


Fast Decline of Scattering Signal from small defects

Shrinking design-rule out-pace optical resolution and scattering limits

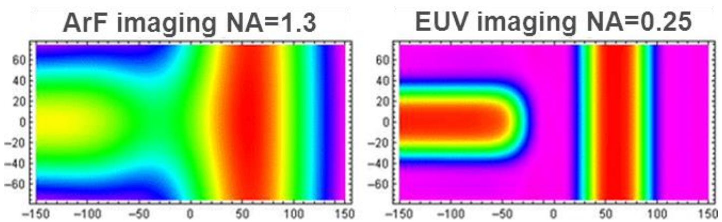
Inspection Cannot Follow Litho Progress Anymore

All Methods Beyond Dry 193nm are not useful



Gupta et al; Performance-driven optical proximity correction for mask cost reduction. J. Micro/Nanolith.

ADVANCED OPTICAL TECHNOLOGIES, DOI 10.1515/aot-2012-0124



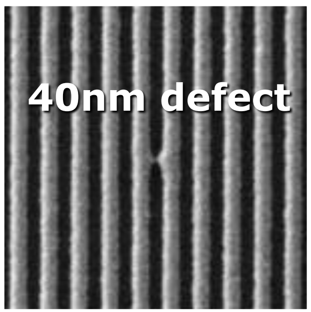
http://www.nikonprecision.com/newsletter/fall_2008/article_05.html

Optical Tricks – Scratching the Bottom

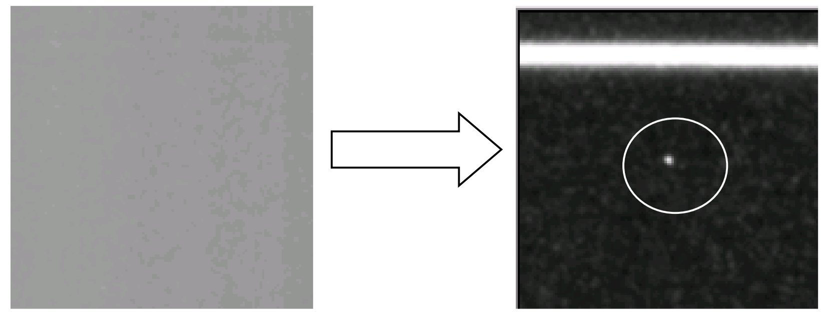
Using Non-Standard Optical Imaging Techniques

High resolution Dark Field, polarization, interference etc

SEM Image

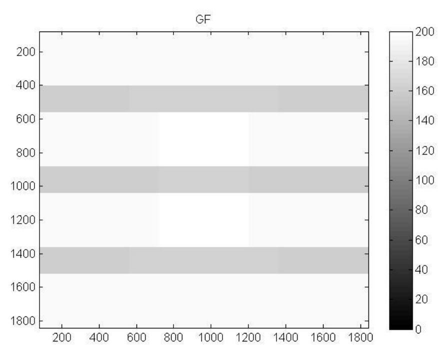


Imaging

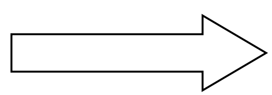


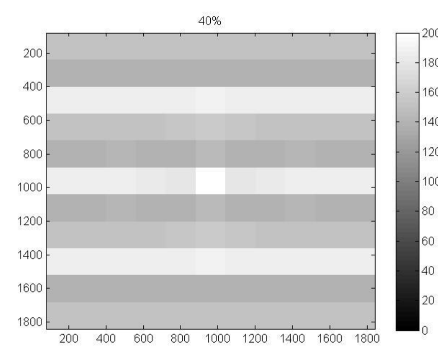
No Resolution

SNR 25



Optical Contrast & Resolution Enhancement





Utilizing Every Possible Physical Property of Light to Improve Imaging

Mostly Never Used In High Speed Imaging !

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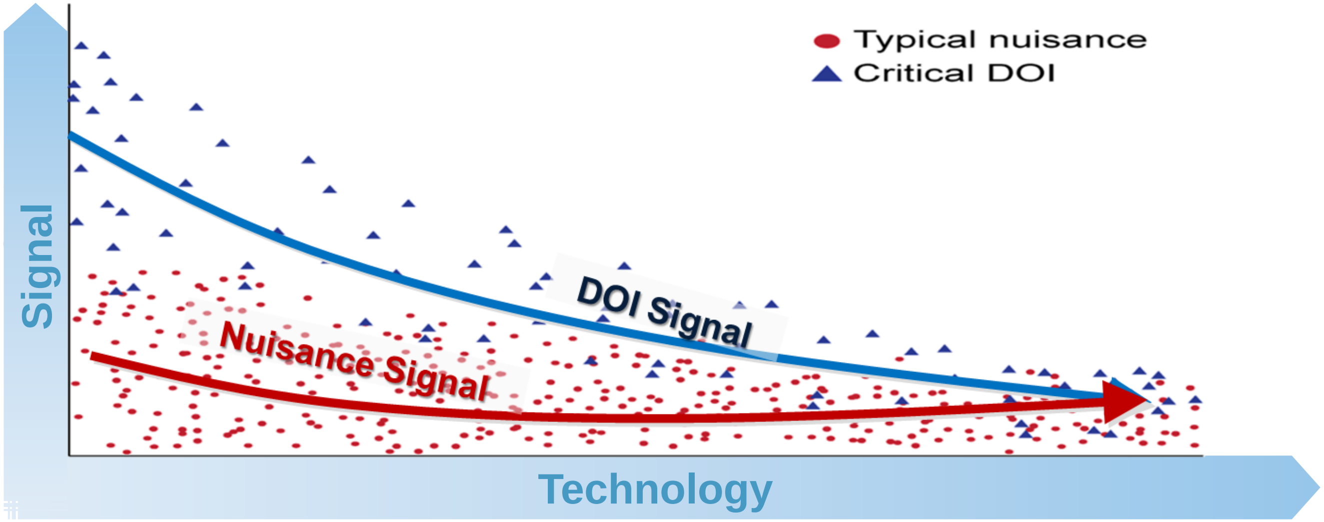
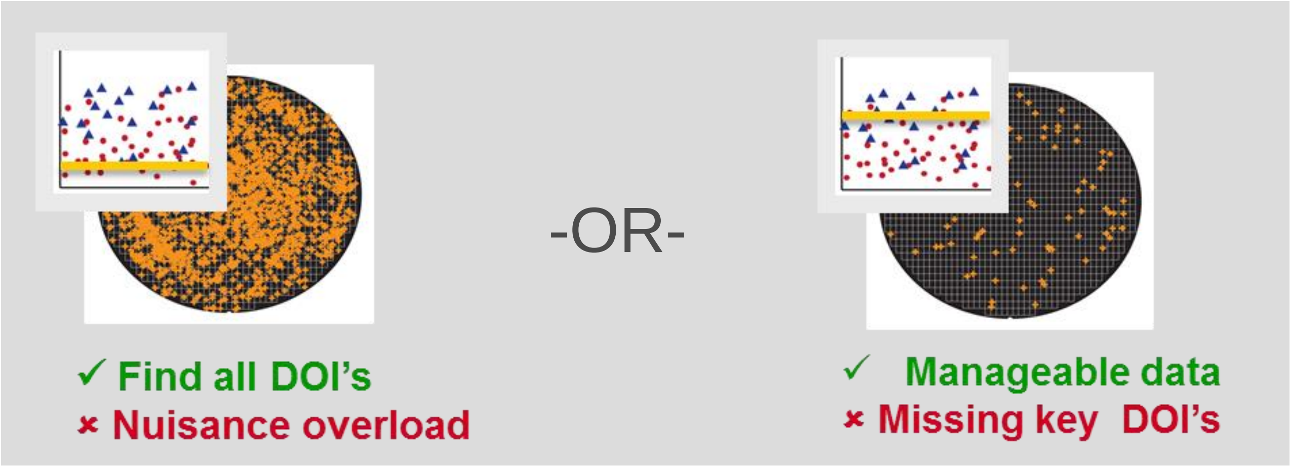
Wafer Inspection @ High Noise Conditions



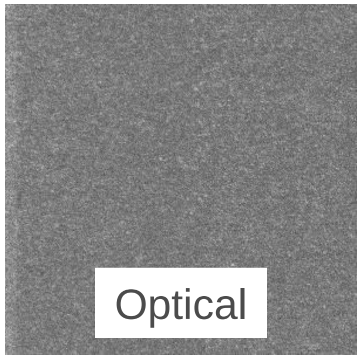
Defect signal decreasing faster than nuisance signal

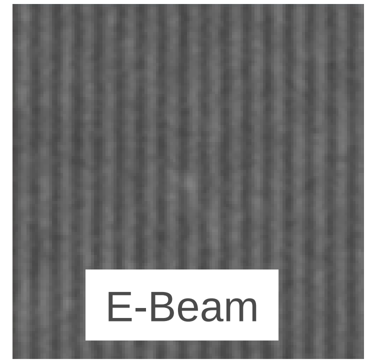


➔ **Inspection needs to address high nuisance rate**

Gaining Back the Resolution

e-Beam Inspection





Fundamental Physical Difficulty: electron interaction.

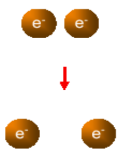
Solution requires massive parallelism and is ‘engineering heavy’

Coulomb Interaction

Boersch Effect

- Electrons repel each other in the beam direction
- Causes energy spread among electrons
- Result in chromatic aberration

Loeffler Effect

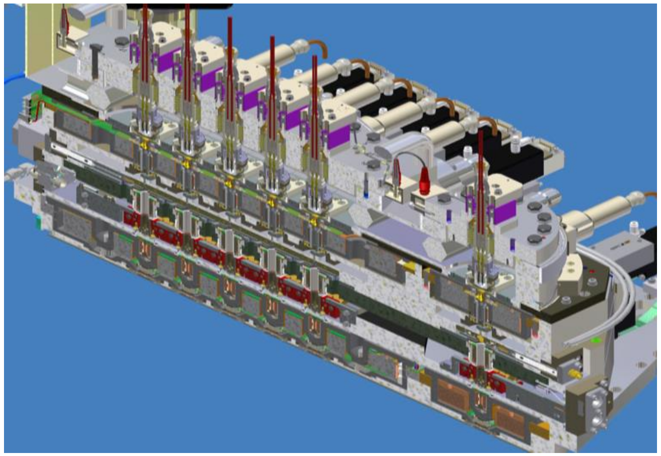


- Electrons repel/collide each other in the radial direction
- Causes trajectory change and energy spread among electrons
- Result in chromatic as well as spherical aberration

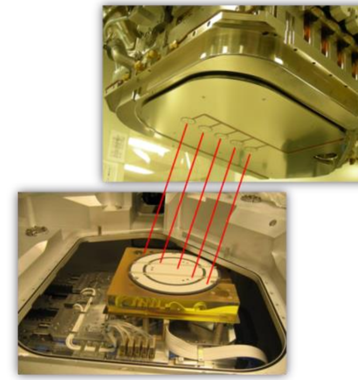
No ‘Technology Wave’ to Ride and Leverage

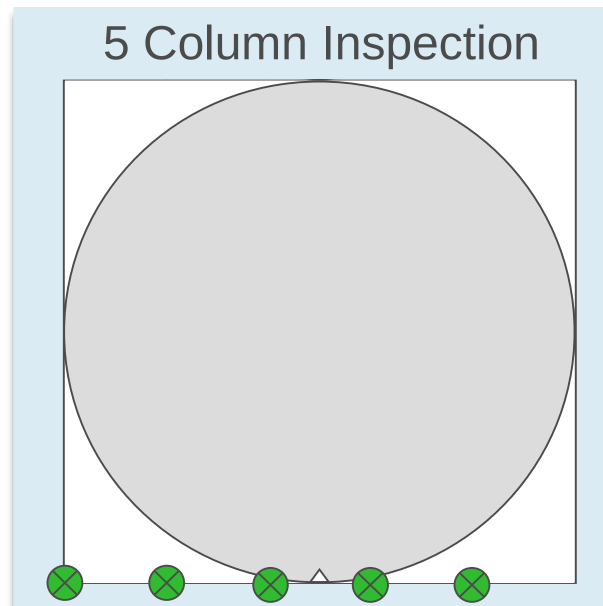
eBeam Parallelism #1: Multi Column

High-TPT E-Beam Inspection using novel architecture



5 Columns packed at wafer width



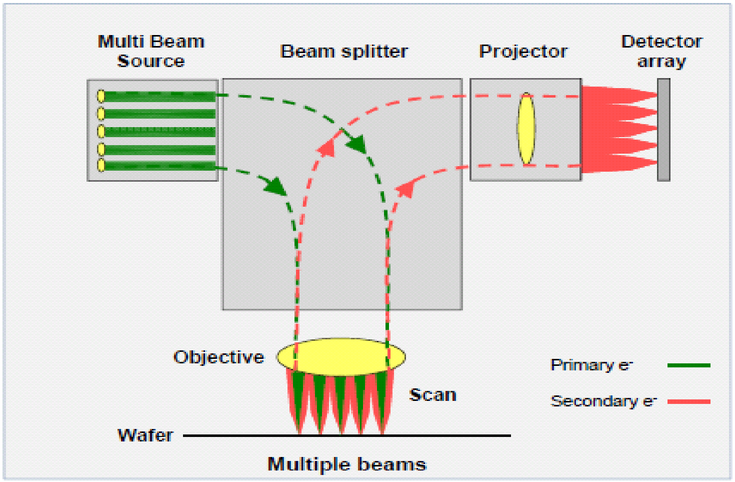


eBeam Parallelism #2: Multi Beam

Joint (old) AMAT-Zeiss program

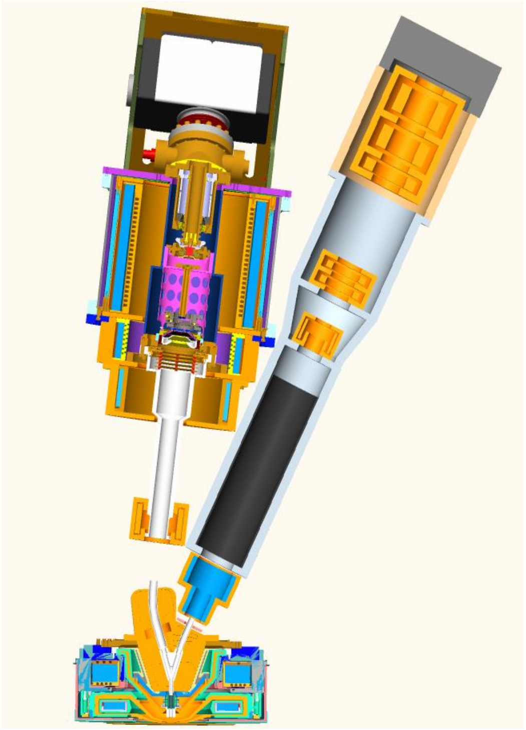
Column control

Column electronics



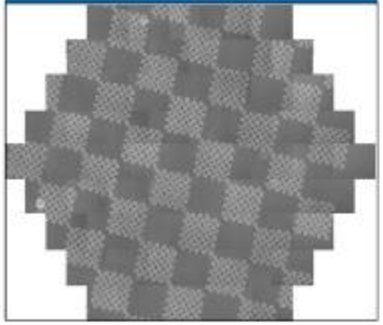
Parallel detection

Fast image acquisition

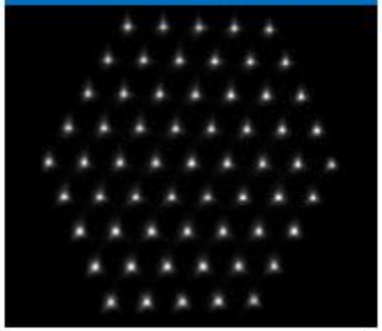


mSEM Demonstrator

High Throughput by Parallel Image Acquisition

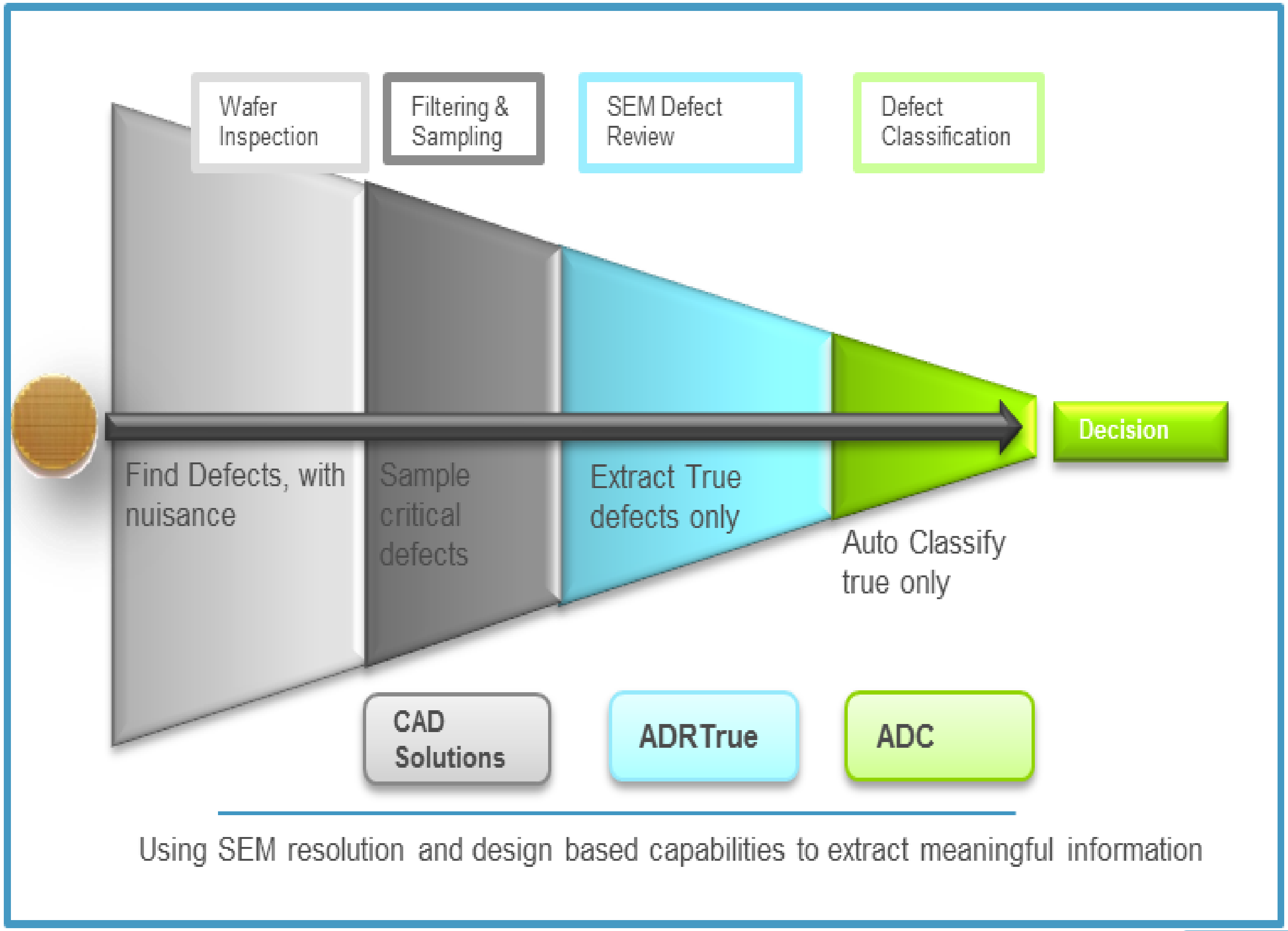


High Efficiency Detection of Secondary Electrons



Hybrid Solution: Optical and EBI

Combining the standard solutions with additional data CAD, hot-spot etc

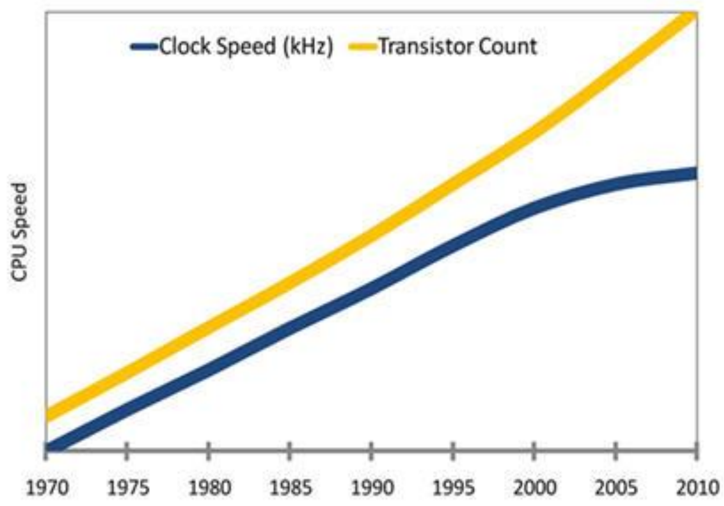


Computation Challenges

- Inspection data rates grow X20 every 10 years
- Algorithm complexity grows as well. ~ 4X every 10 years

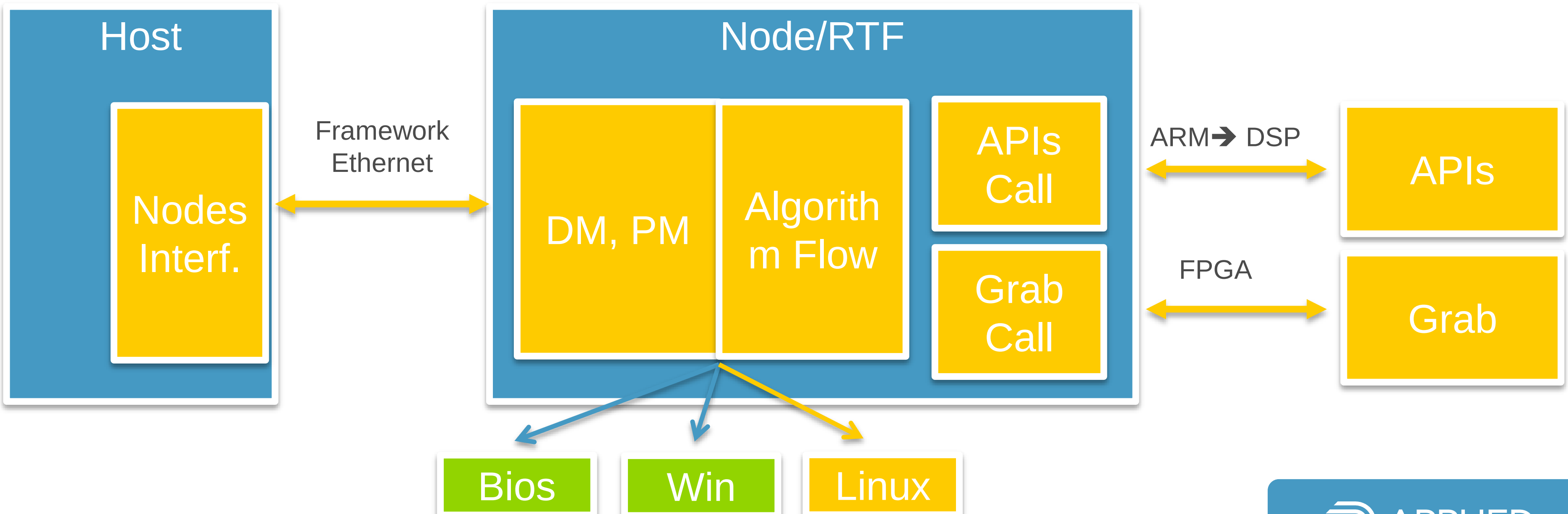
- Computing technology: single core performance improves at low pace
  - Clock speed increase stopped
  - Vector performance improves slowly
- Result: Exploding increase in number of compute nodes

- Problem:
  - Significant system complexity
  - Increased overheads
  - New bandwidth bottlenecks



Required Solutions

- Maintain cost-performance
- Enable flexible system design
- Leverage the progress in computing platforms
  - More cores
  - Larger vectors
- Easy migration between generations
- Infrastructure example:



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Summary

- Inspection technologies encounter key technical difficulties
- A transition to high speed EBI technology is needed, combined with optical inspection and sampling
- Solution providers carry all the burden of the technology development. No ‘assistance’ from Litho anymore

- Computing platforms made significant progress with the aid of Moore’s law
- However, increased design complexity is in the heart of HW/SW design, and continue to increase

Turning innovations
into industries.™

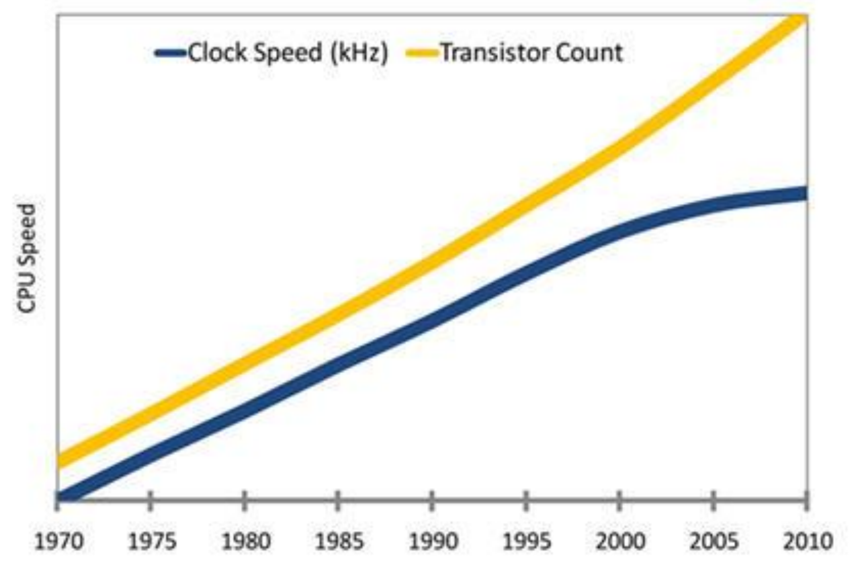
Computational Difficulty
Increased Parallelism

Processor Clock Speed had Stopped at ~3GHz

Performance Gained by Other Improvements

- Multi-Core
- Wider SIMD

Also in DSPs, Even Stronger Trend in GPUs

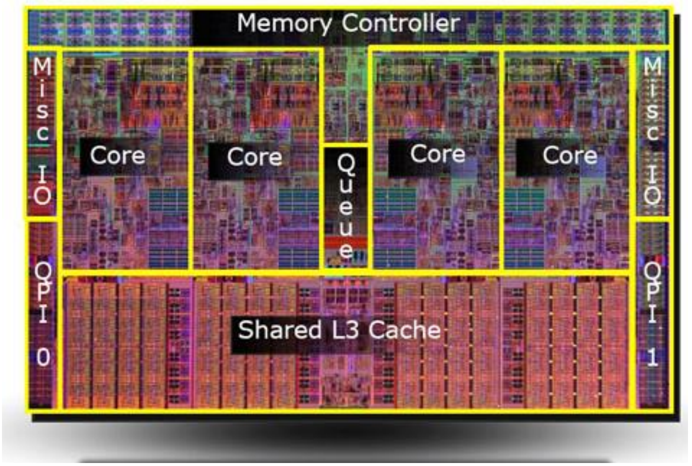


Ever Increasing data rates and algorithm complexities require more processing

Massive parallelism is needed with its many issues

High speed communication

Parallelism overheads (data distribution, BW etc)

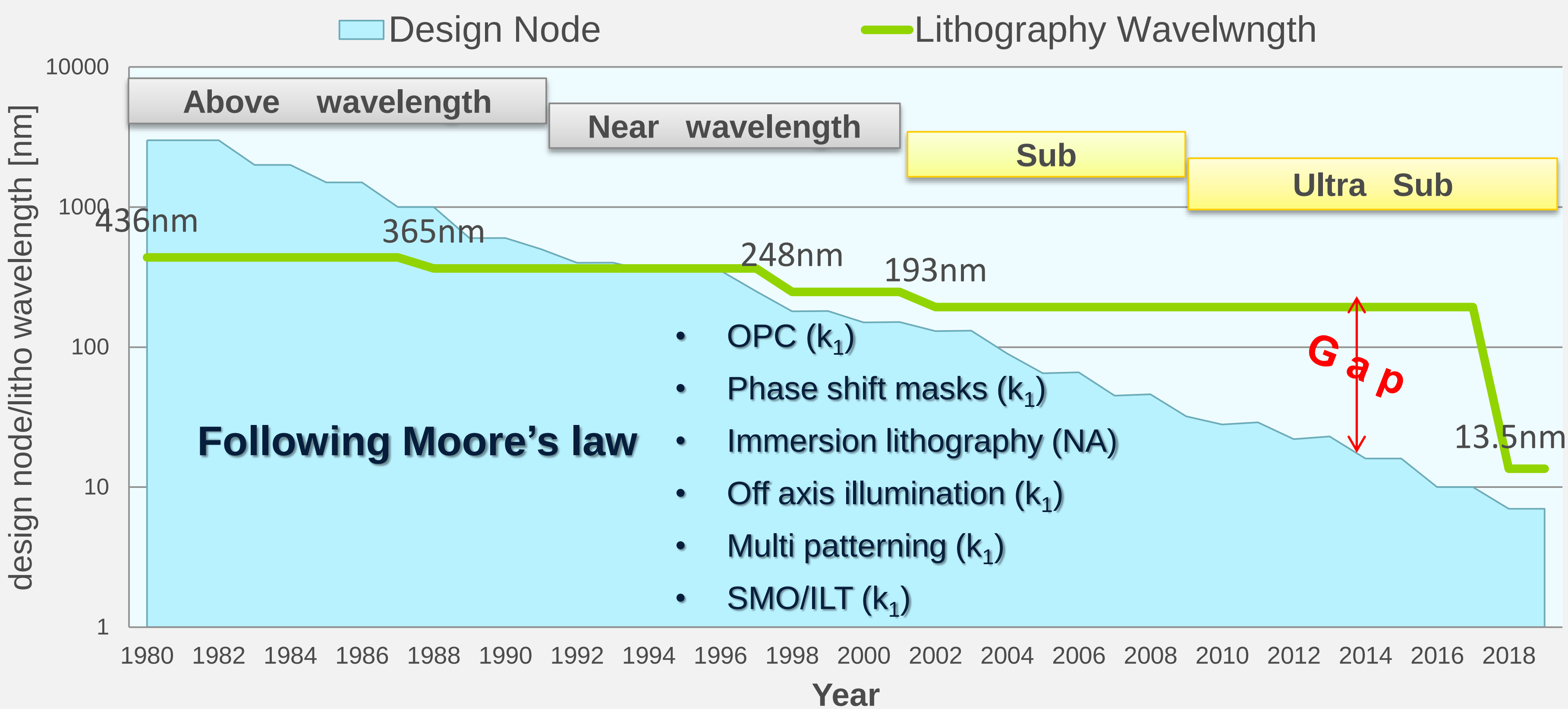


Flow

- Imaging: Historically – riding on litho technology
  - This has ended. No imerssion, no EUV
  - Needs to go to EBI
    - Challenges in speed
    - Needs MC or MB or both
- Computing
  - Exponential growth in data-rate and algo
  - Processor speed has reached limits
  - Spreads in cores and vector
  - Much more complex systems architecture – needs scalable architectures

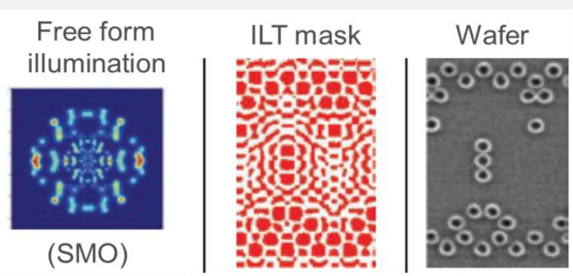
The Lithography Challenge

$$R = k_1 \frac{\lambda}{n \cdot sin\theta} = k_1 \frac{\lambda}{NA}$$

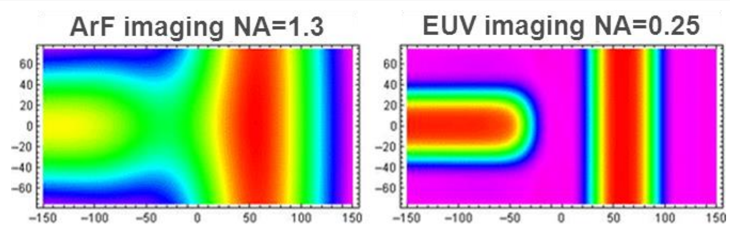


Optical proximity corrections (OPC)

Gupta et al; Performance-driven optical proximity correction for mask cost reduction. J. Micro/Nanolith.



ADVANCED OPTICAL TECHNOLOGIES, DOI 10.1515/aot-2012-0124



http://www.nikonprecision.com/newsletter/fall_2008/article_05.html

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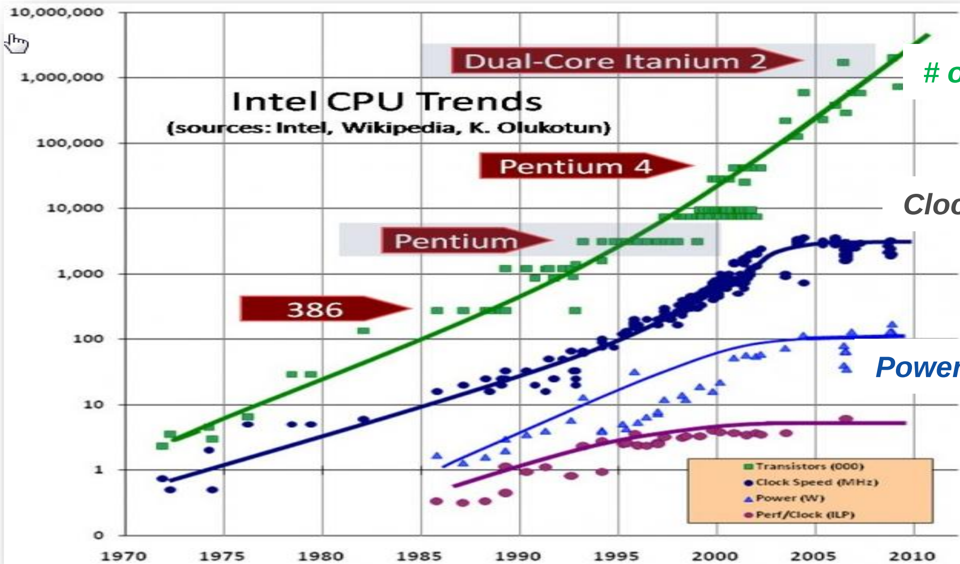
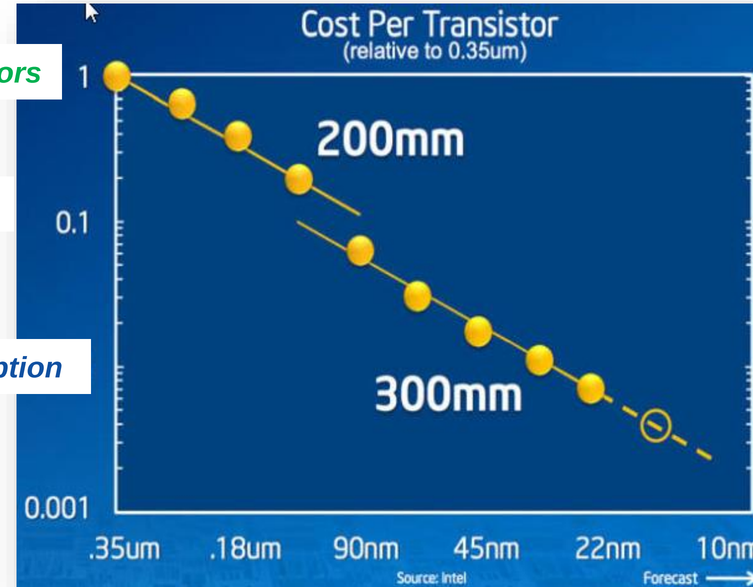
The Cost Challenge

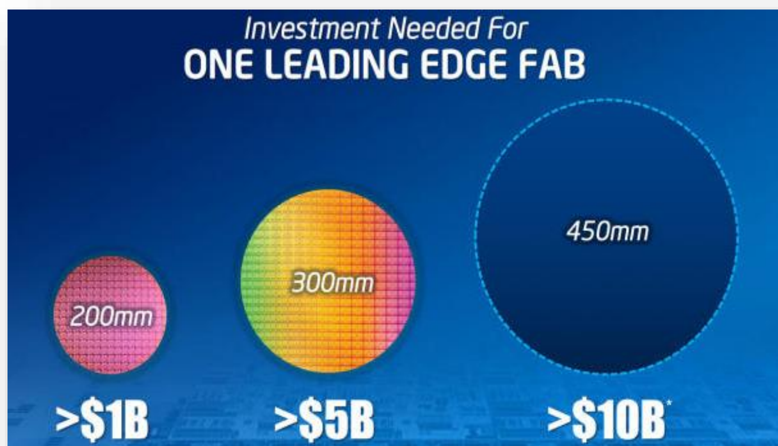


Source:www.extremetech.com/computing/116561-the-death-of-cpu-scaling-from-one-core-to-many-and-why-were-still-stuck



Source: on the Moore's Law hot seat: Intel's Mike Mayberry, CNET, 2012

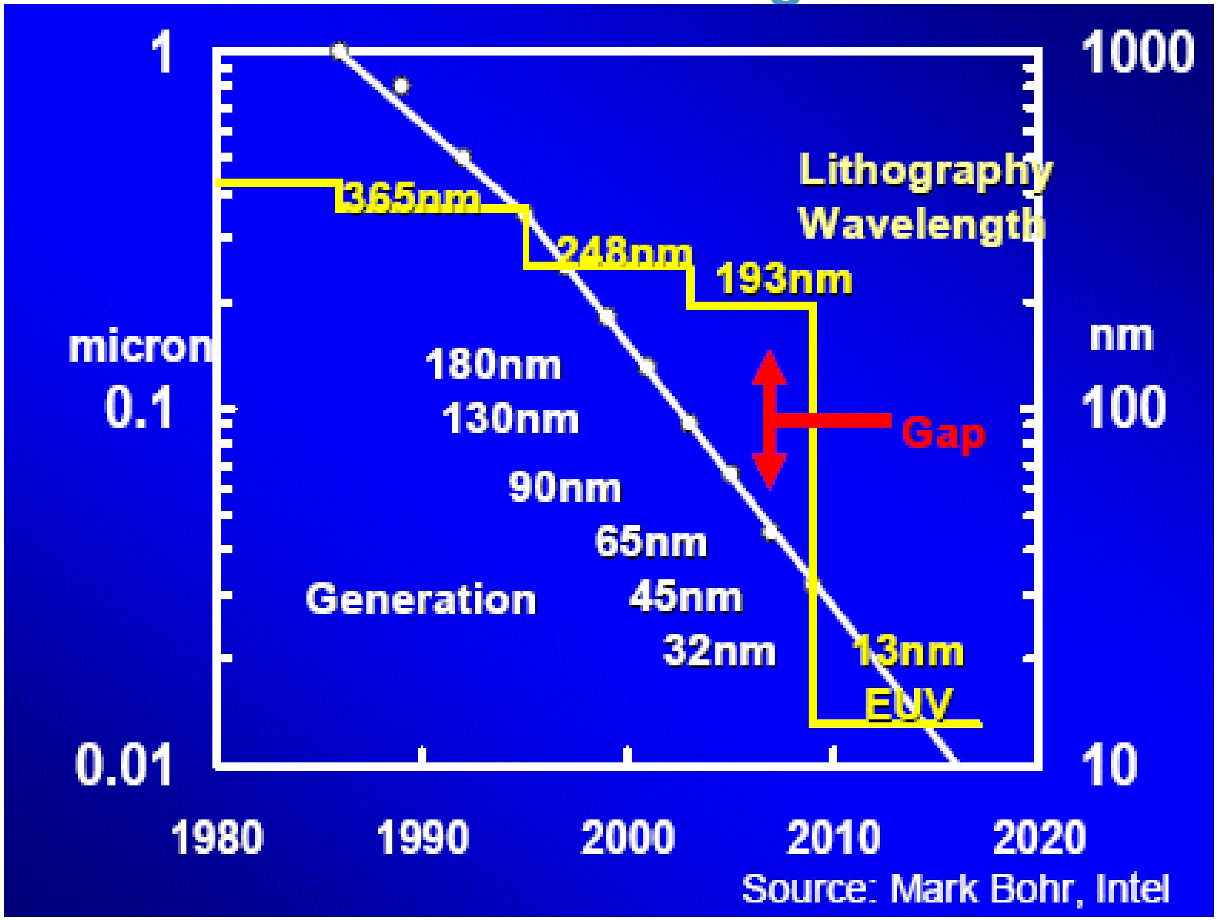
Complexity Increases Cost has to go down



Increasing wafer size while maintaining tools' CoO can reduce cost of chip

Inflection Point #1

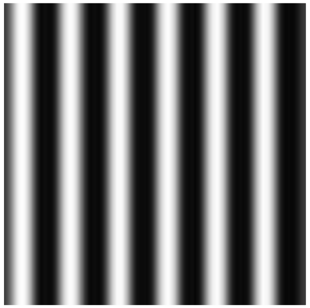
No Shorter Wavelength for us



No shorter wavelength beyond 193nm for Litho (and Imaging)

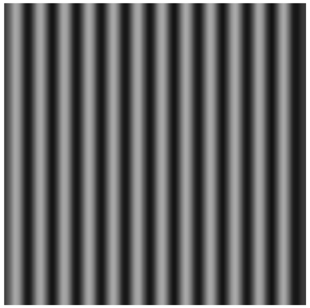
The Result: No Resolution

f=0.5*NA/λ



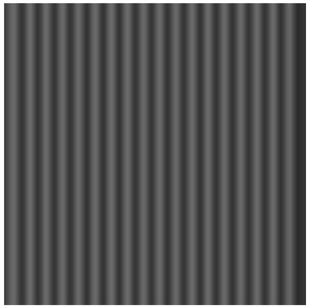
DR: 250nm

f=1*NA/λ



DR: 110nm

f=1.5*NA/λ



DR: 90nm

f=1.9*NA/λ

DR: 70nm

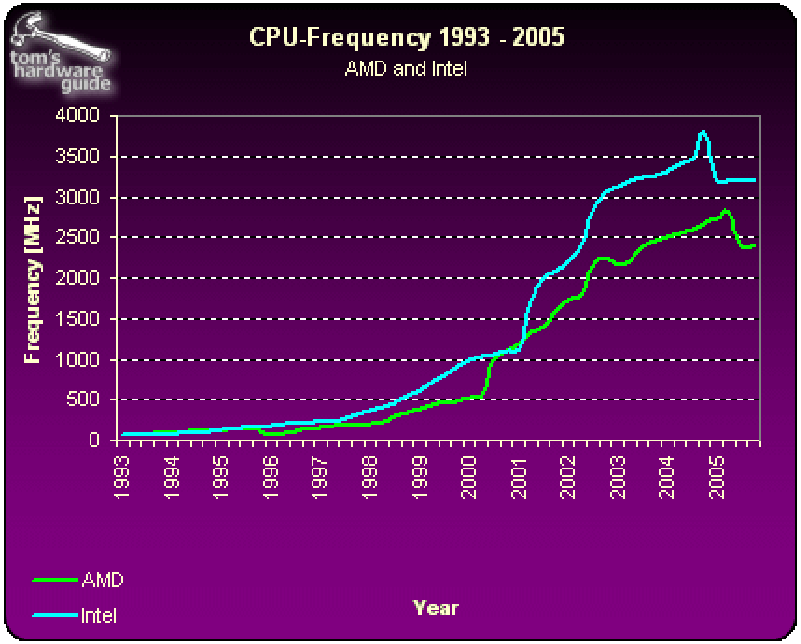
DR: 55nm

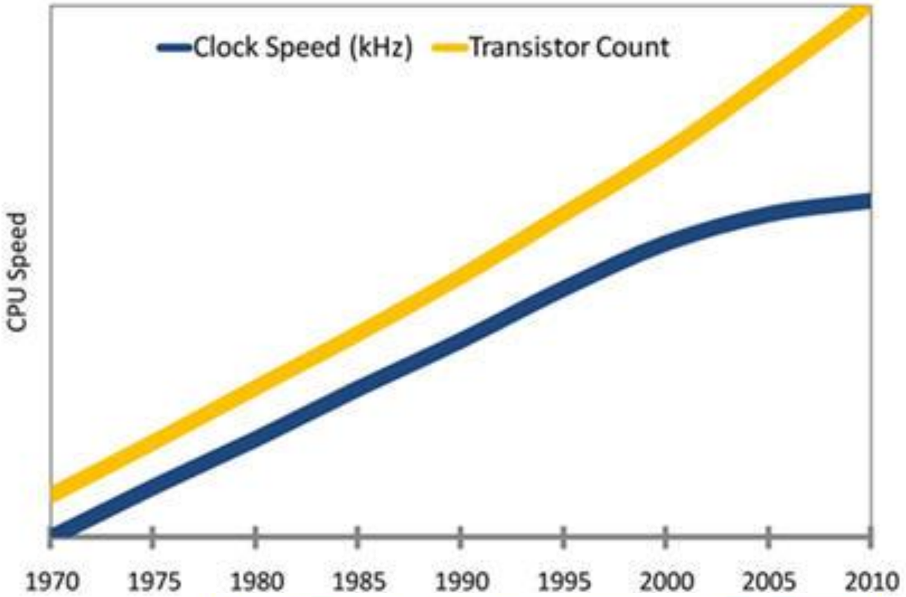
No Resolution

No resolution for $f > f_{cut\text{-}off} = 2NA / \lambda$

Inflection Point #2

The Clock Had Stopped !



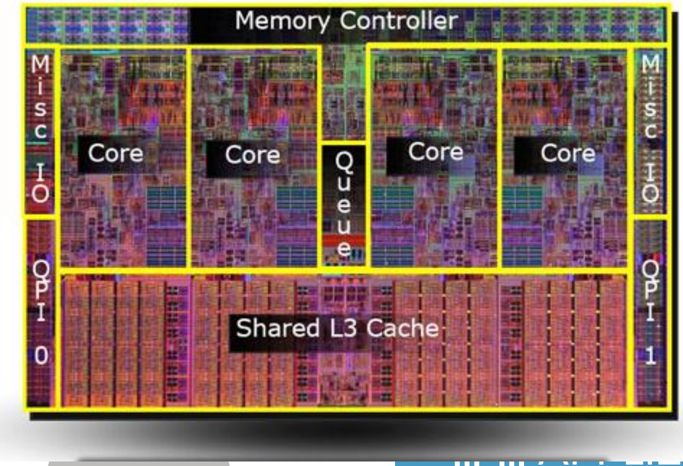


Processor Clock Speed had Stopped at ~3GHz

Performance Gained by Other Improvements

- Multi-Core
- Wider SIMD

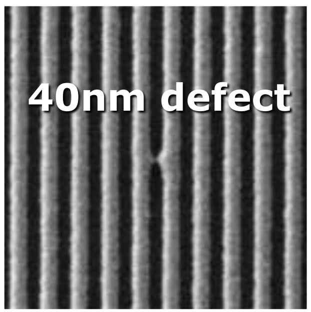
Also in DSPs, Even Stronger Trend in GPUs



What to Do #1: Overcome Resolution Limits

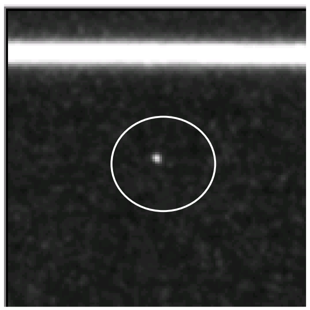
Using Non-Standard Optical Imaging Techniques

SEM Image

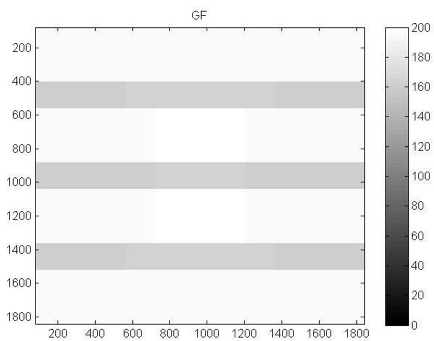


Imaging

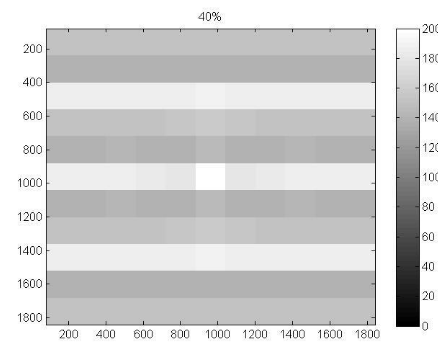
No Resolution



SNR 25



Optical Contrast &
Resolution Enhancement



Utilizing Every Possible Physical Property of Light to Improve Imaging

Mostly Never Used In High Speed Imaging !

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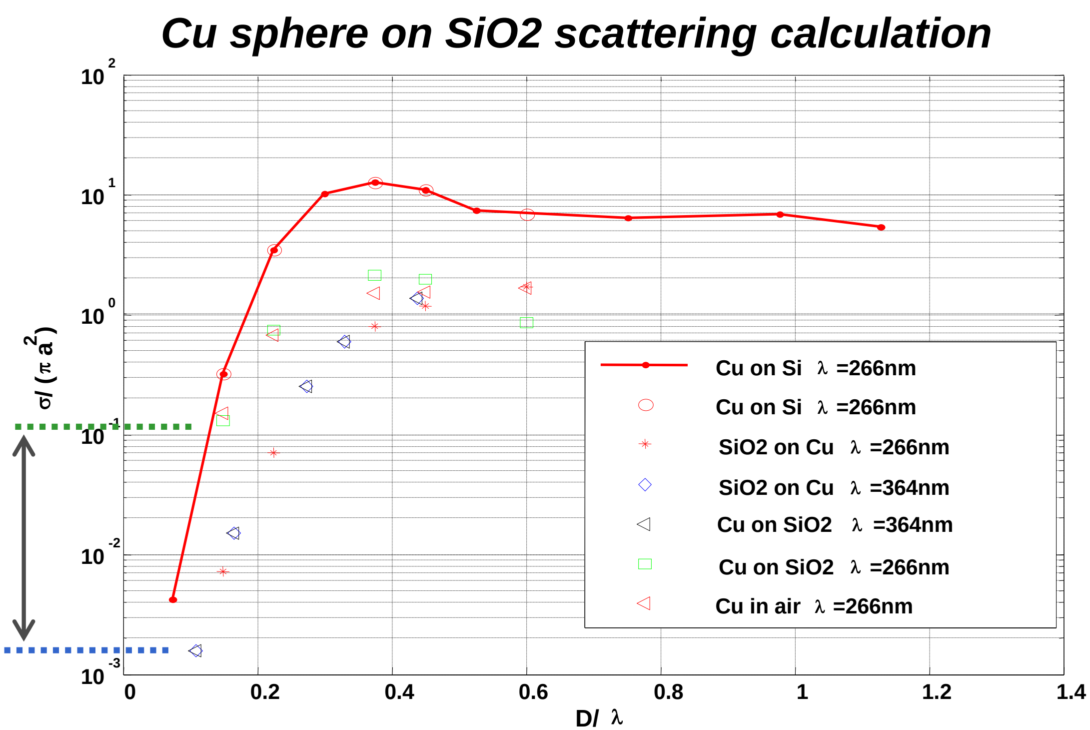
The Scattering Problem – Rayleigh Limit

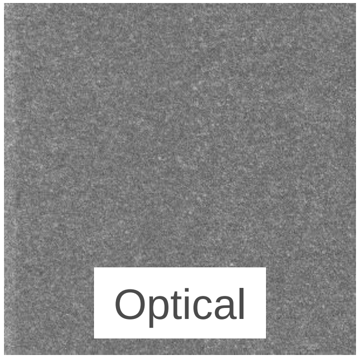


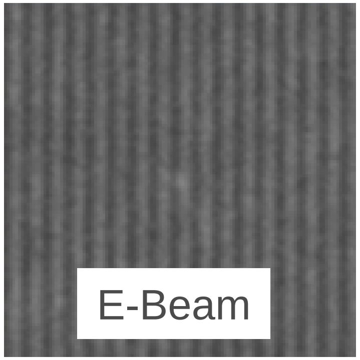
Scattered light falls very fast for small features

Making the Imaging Challenge Very Hard

Always the Next Generation: E-Beam Imaging

Gaining Back the Resolution



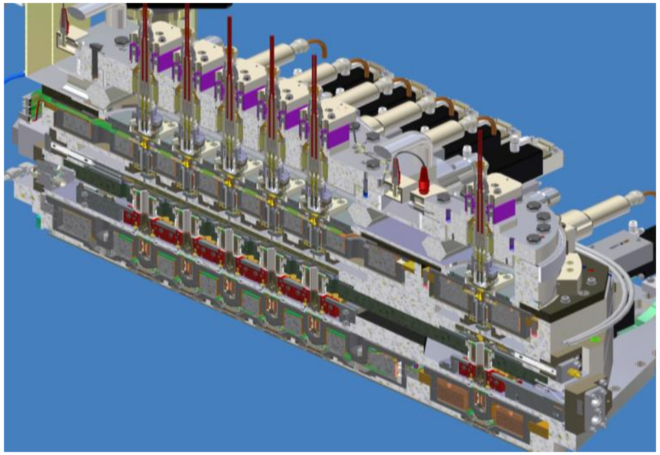


This technology is not fully developed for high-speed imaging

No ‘Wave’ to Ride and Leverage

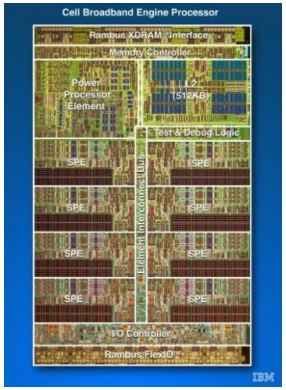
Fundamental Physical Difficulty: electron interaction.

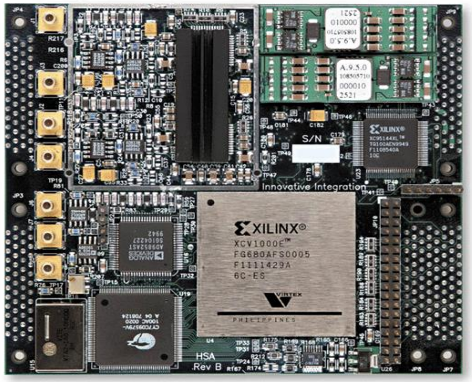
Solution requires massive parallelism and is ‘engineering heavy’



What to Do #2: Leverage Computing Trends

High Performance Computing Takes Many Directions





Cannot Predict Which Will Be the Best In Every Generation

Need to Create Flexible Environment

- Easy to change and mix different Technologies
- Hide the Complexity and drawback of each one

Need to Virtualize Stronger Processors

- Hide the split behind better connectivity
- Infrastructure to leverage the power

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Conclusion

- No Straight-Forward ‘Pulling’ Technology
- New methodologies and concepts are needed
  - Imaging
    - New Techniques
    - SEM based
  - Computing
    - Creating Virtual Faster Processors
    - Establishing Infrastructure for Improved Flexibility

Need to Combine Joint Industrial Effort to Push Technology Forward

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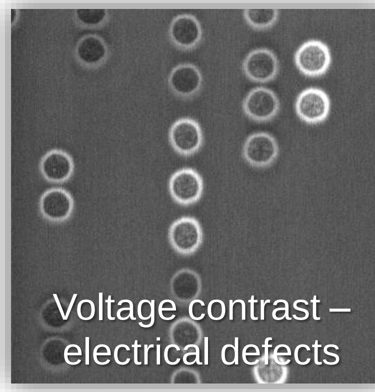
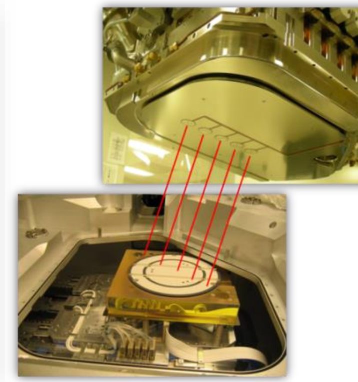
EVision™ E-Beam Inspection

High-TPT E-Beam Inspection (EBI) for 3D NAND

Core technology

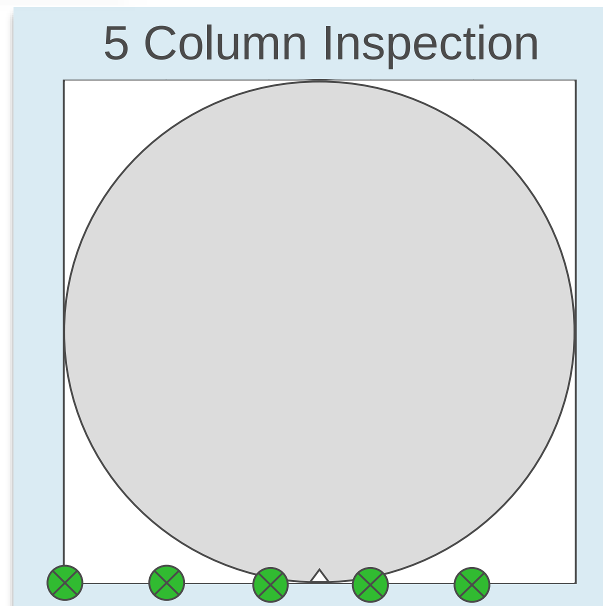
- Revolutionary architecture – 5 parallel detection channels
- Fastest A/D channel with data rate up to 6000 MPPS
- High probe current





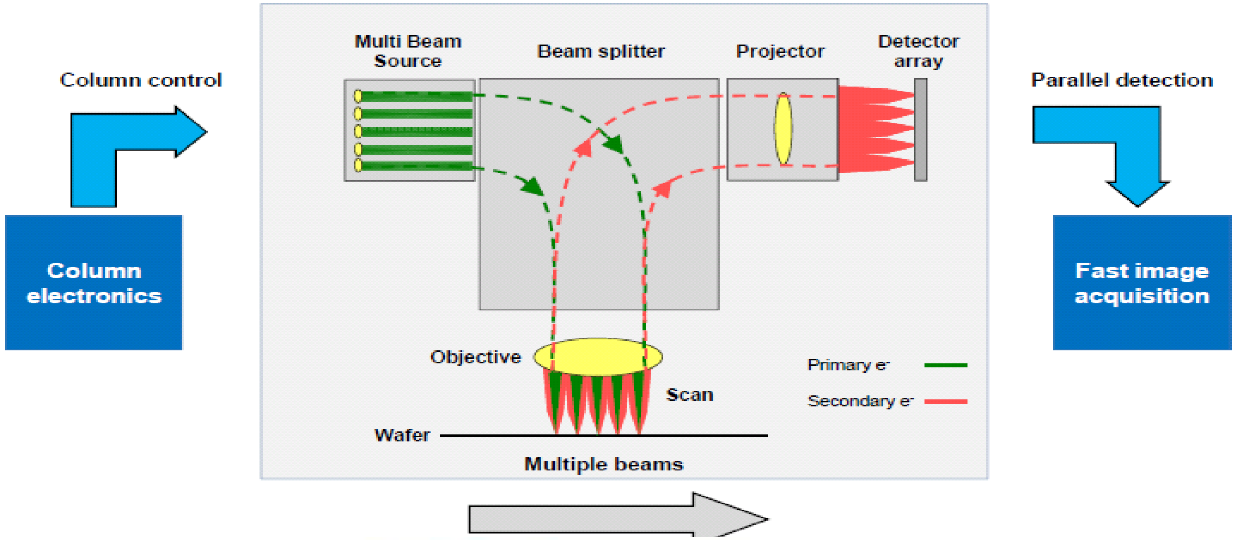
Benefits

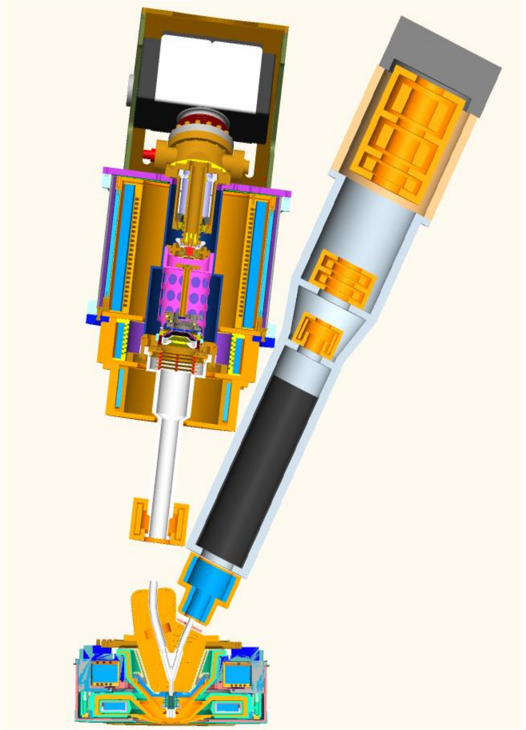
- Electrical defects sensitivity
- Production TPT
- Production stability



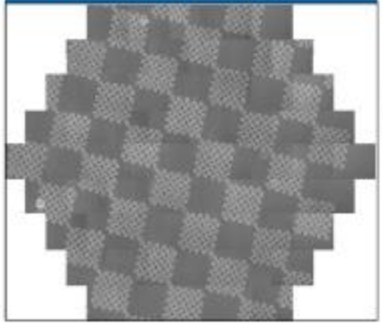
UHRIS – Joint AMAT-Zeiss Program

Technology Highlights



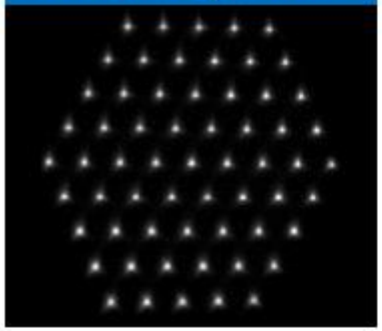


High Throughput by Parallel Image Acquisition



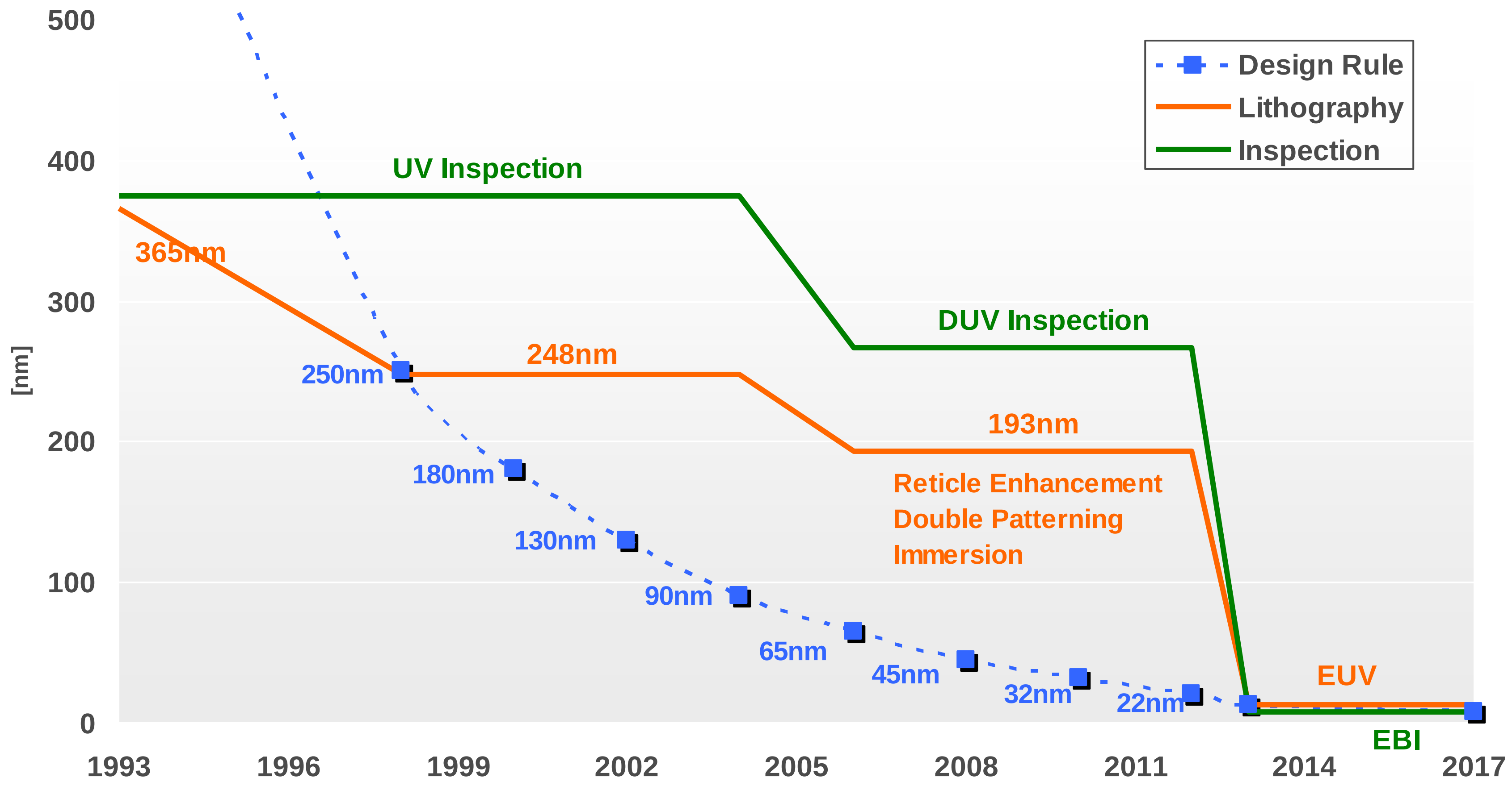
mSEM Demonstrator

High Efficiency Detection of Secondary Electrons



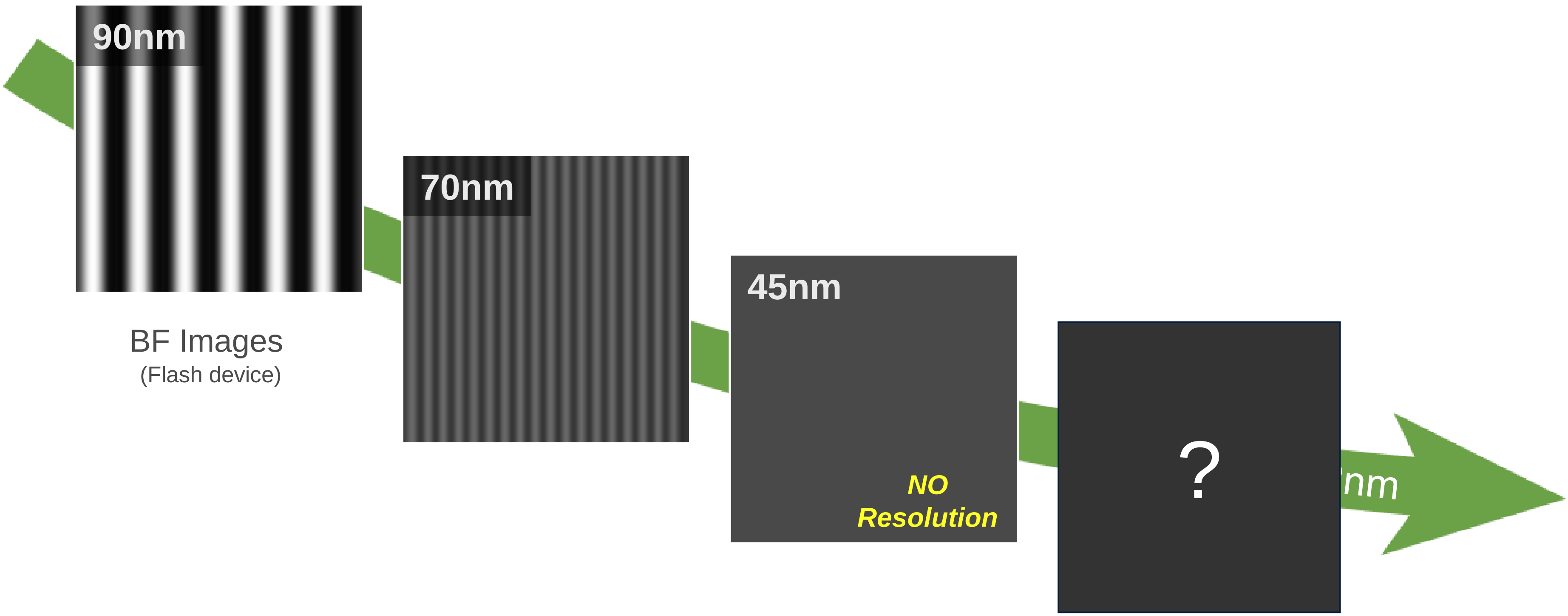
- Programs Started 2002
- Joined work stopped 2011
- Zeiss continue with the technology for life-science applications

Sub-Wavelength Lithography



Inspection follows the Lithography footsteps

End of Optical Resolution?



Straightforward BF imaging reaches its limits at sub-45nm design rules

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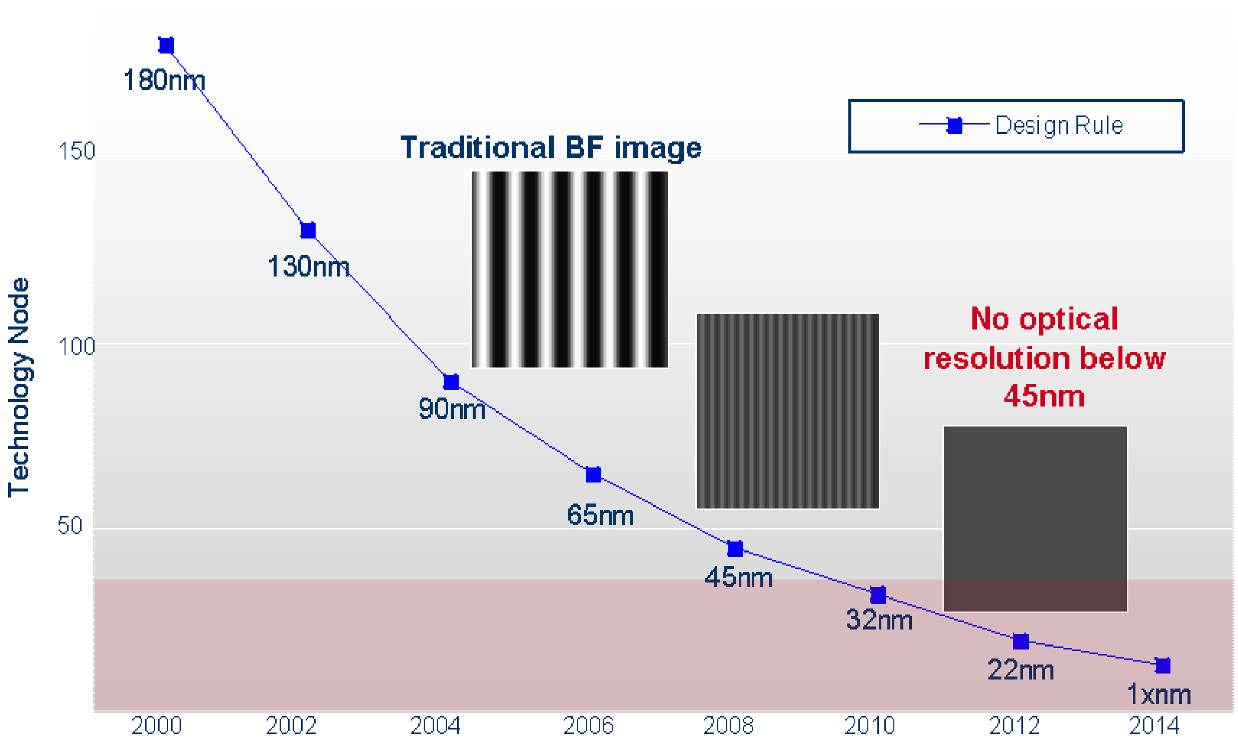
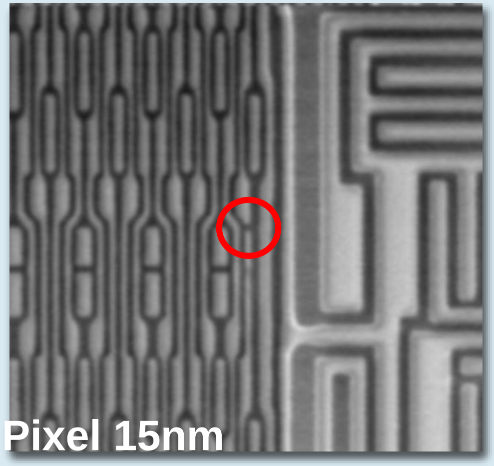
Optical Inspection – End of Resolution



No inherent sensitivity limitation for Electron-Beam technology

Available solutions have limited throughput



Multi-Column e-Beam Inspection:
Overcoming the CoO & sensitivity gaps on 2x nm and beyond

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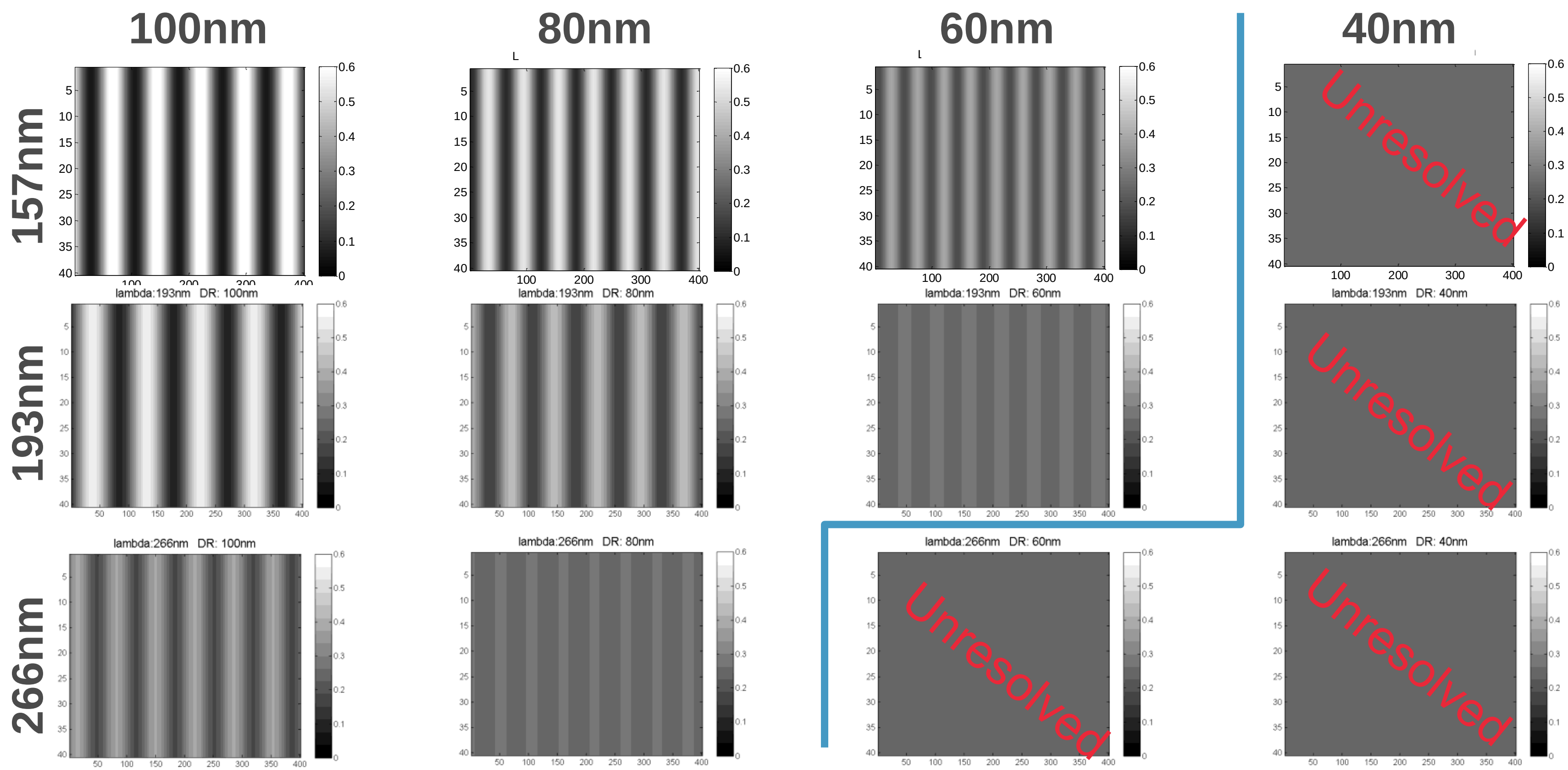
Brightfield Resolution Limits

Simulation



$$R \propto \frac{\lambda}{NA}$$

No brightfield resolution below 45nm for 266/193/157nm

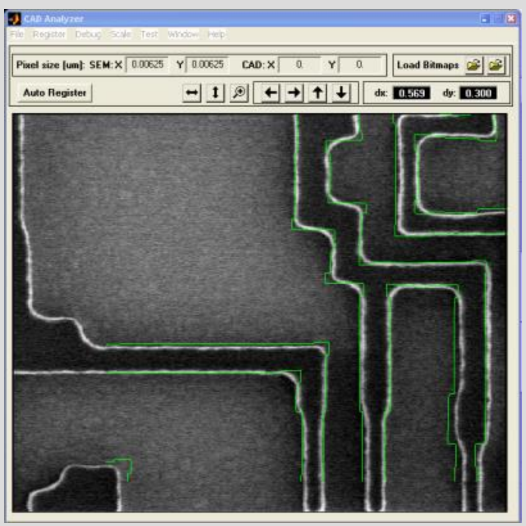
Fundamental Technologies:
Scanning Electron Microscopes

High resolution column (~1nm), High currents (10pA-100nA)

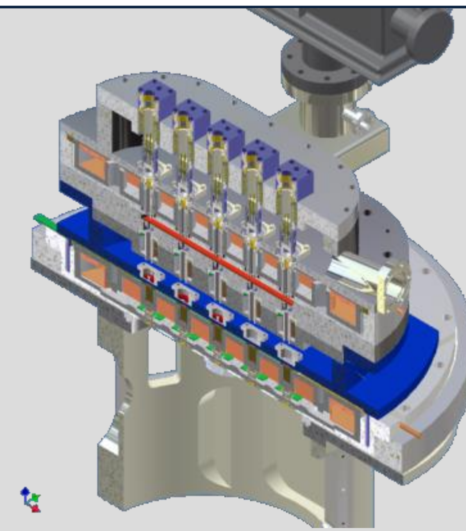
- Design, assembly, calibration

Support modules

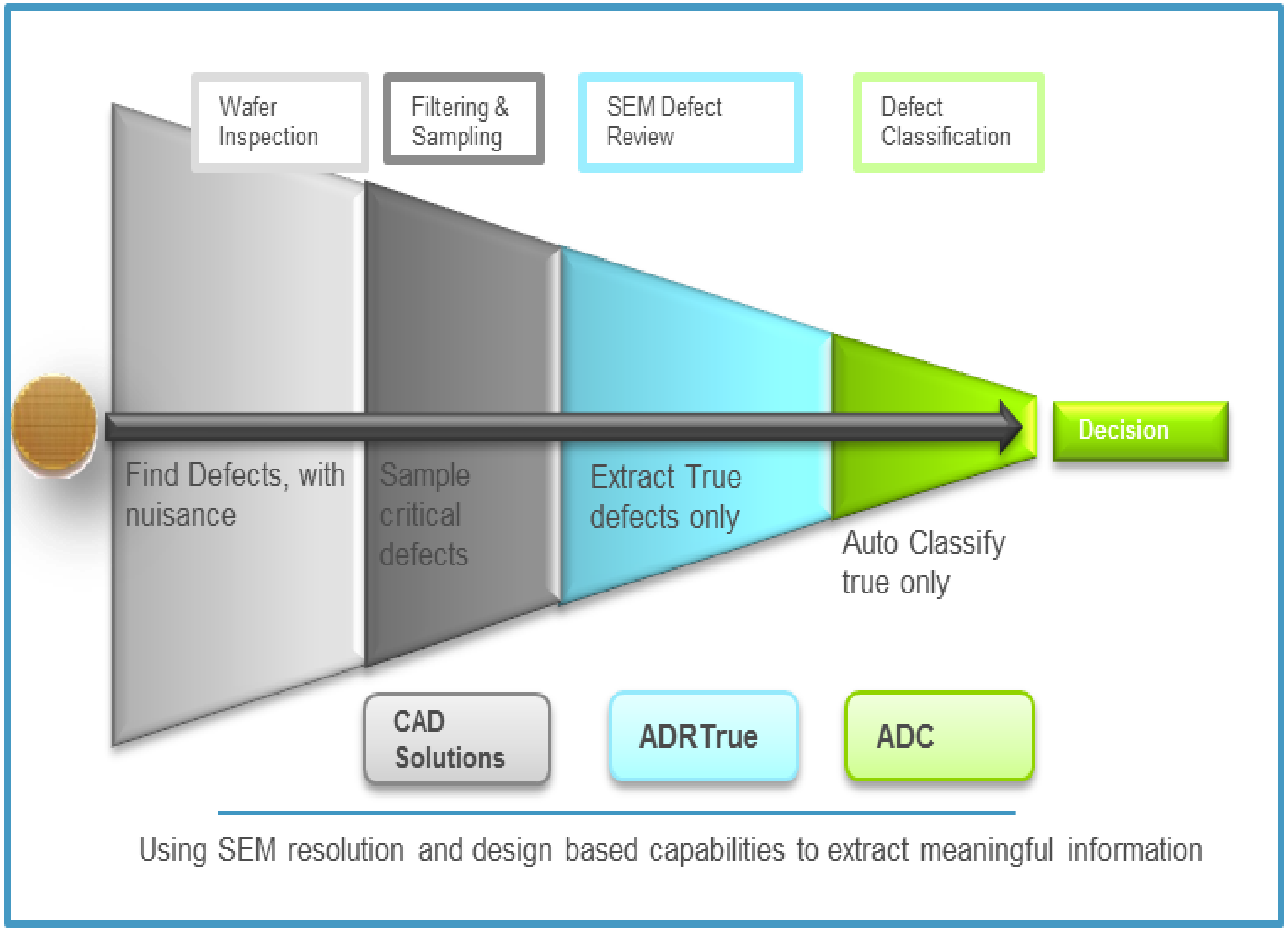
- Detectors
- Scanning



CAD verification on SEM image



High speed, high resolution e-beam scanning and detection head


Wafer Inspection
Filtering & Sampling
SEM Defect Review
Defect Classification
Find Defects, with nuisance
Sample critical defects
Extract True defects only
Auto Classify true only
Decision
CAD Solutions
ADRTrue
ADC
Using SEM resolution and design based capabilities to extract meaningful information